ENGINEERING CASE LIBRARY

ECL 151A

UNDERSEA PIPELINE: VERIFICATION OF A STRESS ANALYSIS

Part A: Building a Bundle of Snakes

The undersea pipeline project of Universal Aerospace Inc.* was well into the detailed design stage, in the spring of 1969, when Rob Kinner joined the group. Rob, a forty-year-old civil engineer (Stanford'53), normally divided eighty hours a week about equally between a doctoral dissertation at Stanford University and his job in Universal's Structural Analysis Department. Somehow in this double life, Rob managed to sandwich such family duties as yardwork; a fact that Universal came to appreciate, as will be shown.

*Names in the case have been disguised.

 Prepared for the Stanford Engineering Case Program by Dean C. Ing with the support of the National Science Foundation.

Rob's temporary assignment with the undersea pipeline project came about when their project management people began to have doubts about a major design detail. Precisely because Universal's interests are universal, it is possible to call on specialists of many disciplines within the company for short-term assistance on a given project. The project leaders must be willing to pay the specialist's wages from project funds, however, which keeps such personnel loans at a minimum. In this case, they felt that a specialist in stress analysis would be worth his wages. When his manager mentioned this request for a trouble-shooter, Rob volunteered.

Rob was introduced to the job by project engineer Jay Hardin. Jay knew from experience that Rob would have a better grasp of the problem with a general understanding of the project, and invested a day in giving Rob this background.

The details of drilling and capping an oil well under 1200 feet of salt water were passed over lightly. Universal's pipeline project began with a completed wellhead, which is a concrete pad set into approximately level sea floor, over the drilled well, with a set of four capped two-inch pipe stubs protruding from the concrete. All that was necessary was to attach more two-inch pipe to these protruding pieces, and pump the crude oil away through this pipeline bundle. Though there are four pipes, one is used as a gas bleed line and one is a spare. The remaining two pipes carry the crude oil.

But it simply is not practicable to suspend the pipes from a barge floating above, due to inclement weather problems. It might be possible to erect some sort of "Texas Tower" arrangement from the sea floor like a derrick, but the cost in 1200-feet depths would be prohibitive. Universal's pipeline project had come up with another idea: Instead of erecting a pumping station directly above the wellhead, they proposed to sink a pumping station and anchor it to the sea floor, perhaps thousands of feet away from the wellhead. Such a pumping station could handle the output of several wellheads, spaced around the station.

When Jay unrolled the top assembly drawing of the wellhead scheme, Rob began to see why he was needed. Conceptually it was simple, as Figure 1A shows. A steel caisson, called a <u>wellhead cellar</u>, was fitted with attachments both for anchoring to the concrete wellhead below and for mating to a manned service module above.

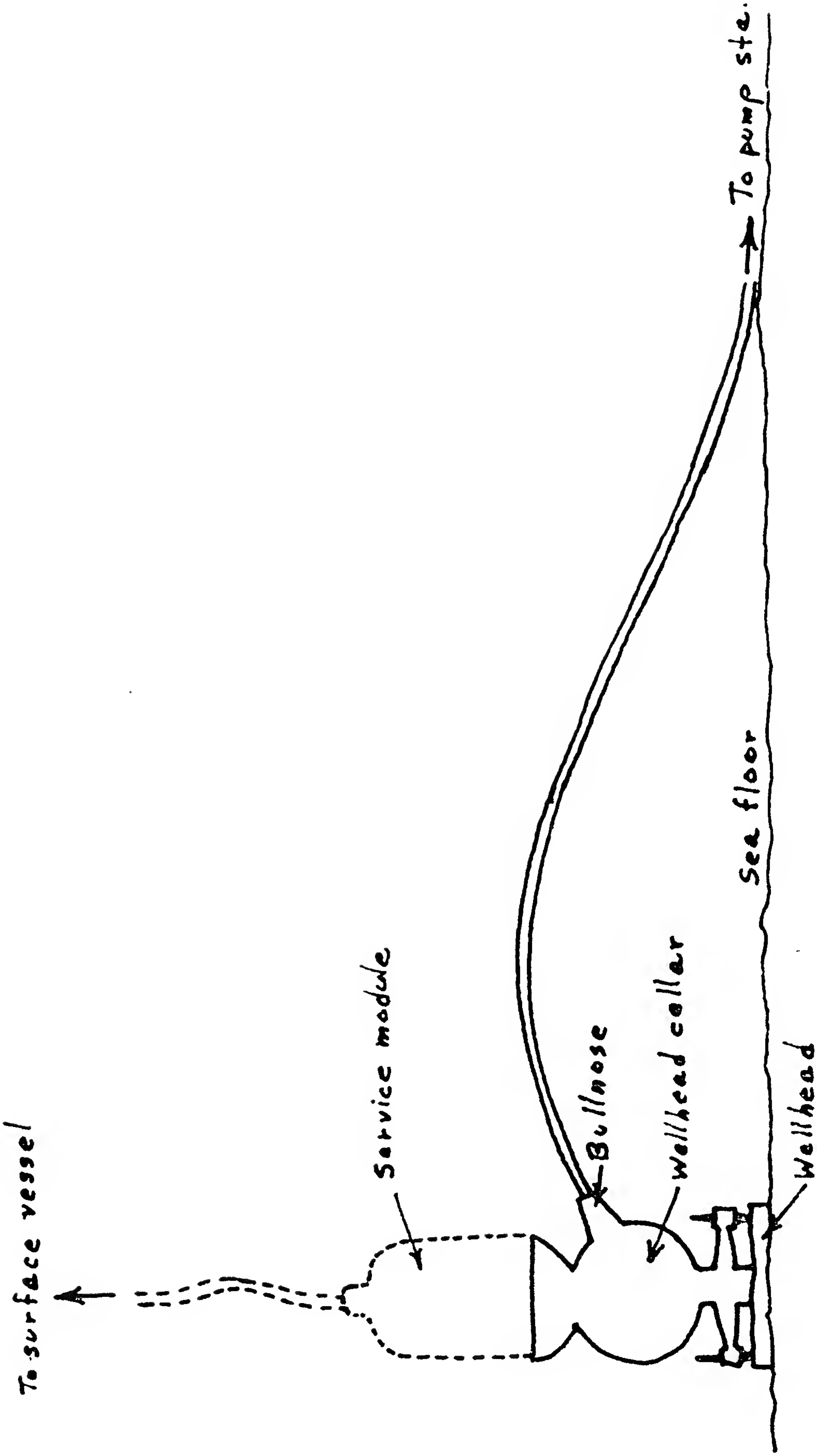
To pump sta.
Sea floor
Service module
Bullnose
Wellhead collar
Wellhead
To surface vessel

FIGURE 1A

The wellhead cellar's working area was a ten-foot ball; and once attached to the wellhead, it would be a permanent fixture there. The service module, lowered like a diving bell, would allow workers to descend through a hatch and into the wellhead cellar where they could work in a dry environment. The essential part of this work was in connecting the stub pipes to another bundle of pipes, called the pipeline bundle, which would lead to the pumping station.

In the detail drawing, Figure 2A, the connected pipes described an arc inside the wellhead cellar between the straight segments emerging out of the concrete and a junction high on the side of the ten-foot ball. The pipes left the watertight junction and arced away in an elastic curve, where they eventually came to rest horizontally on the sea floor, a hundred or so feet away.

Rob was nonplussed by these graceful curves. "You must have a reason for putting such stress on those pipes," he said, running a finger along the "S" curve between the junction and the sea floor. "It would seem so much easier to bring them in horizontally and couple them with elbows."

"That's just it," Hardin grinned. "We can't get away with any elbows because we can't have a radius less than sixty inches in any of the pipe curvatures. Believe it or not, Rob, oil pipelines have to pump hardware, too."

To Rob's questioning frown, Hardin continued, "There are a few peculiar problems with oil pipelines after they've been in service awhile. We have an MTF* requirement of twenty years with this rig. It seems that paraffin in the oil gradually gets deposited inside the pipes, and impedes the flow."

"Like cholesterol in blood vessels?"

"That's pretty close. Well, they've developed some pumpdown tools to cure these problems. One of 'em is a paraffin cutter; it fits fairly closely in the pipe, and they pump it from the pumping station, clear down into the well, and let it come back up again. It reams out the paraffin deposits as it goes, but it won't negotiate a curve of less than sixty inch radius."

"So you're stuck with this bundle of snakes."

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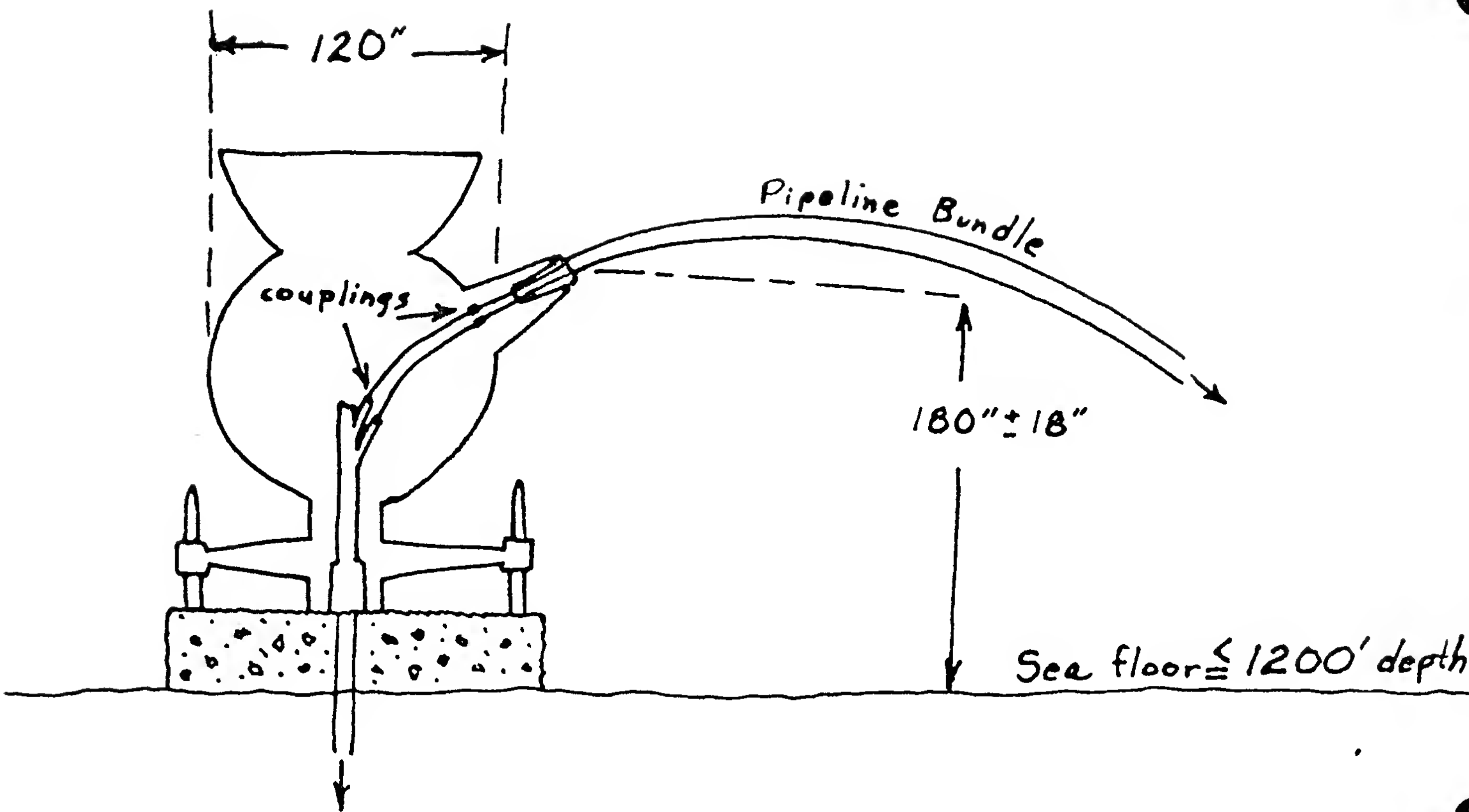
*Mean Time to Failure



Pipe Mat'l : A.P.I. 2 in. pipe, grade J-55

F_t yield, min = 55 ksi

F_t ult, min = 95 ksi

$I = 0.776$ in.^{4}

$E = 30 \times 10^6$ psi

OD = 2.375 in.

ID = 1.995 in.

$q = 0.344$ lb/in., flooded

FIGURE 2A

"You are stuck," Hardin corrected, grinning again. "We have enough room in the wellhead cellar to let us use connecting pipe segments precurved to sixty-inch radii, but each end of that curved segment is straight for the couplings: one end to the segment coming up from the wellhead, the other end to the segment coming in from the bullnose."

'Bullnose' was the jargon term given to the junction hardware in the side of the wellhead cellar. Hardin went on to explain how the bullnose worked. The long pipeline bundle from the pumping station would be floated with buoys and towed into position by a surface ship.

To get the end of the pipeline bundle into the wellhead cellar, a crew manning the cellar first releases a buoy, carrying a nylon line, from the bullnose socket. Another crew at the surface, perhaps twelve hundred feet above, captures this buoy and attaches a steel cable to the nylon line. The wellhead cellar crew then winches in the line and the cable. On the other end of that cable is the pipeline bundle, which terminates in a probe shaped to fit the bullnose socket. When the probe is drawn into its socket and sealed, a set of four, two-inch-diameter pipe ends protrude down into the wellhead cellar at a 20° angle from the horizontal. At this time, the wellhead cellar crew can begin coupling four short, specially-radiused pieces of pipe between the pipeline bundle ends at the bullnose and the ends protruding up from the concrete. The last step is to release the several buoys supporting the pipeline bundle. The bundle then sinks to the sea floor, ready to pump oil. Hardin mentioned that the pipeline bundle design must include a 100% safety factor due to the ocean environment.

Rob steadily collected a set of details on the problem. His jotted notes are summarized in Figure 2A. He studied the data awhile, then returned to Jay Hardin "Correct me if I'm wrong," Rob said, "but you seem to have everything in hand except the stress on the pipeline bundle as it sinks to the sea floor."

Hardin glanced at his drawing board thoughtfully. "Let's say we hope so," he hedged. "What we need from you is an accurate idea whether this 'bundle of snakes' will describe a nice smooth curve without collapsing or going below a sixty-inch radius of curvature. If it's gonna collapse, how can we fix it so it won't?"

"Fair enough," Rob said. "But there's one thing I didn't get clear in my notes. We're stuck with this ah, A.P.I. pipe material. . ."

"American Petroleum Institute," Jay explained. "They have specs on standard steel pipe that the industry's been using for years. We're committed to using it; start specifying special steels and the petroleum industry might lose interest. You can see why, when they're trying to open up a new field using a million feet of pipe and somebody adds a few cents per foot onto the pipeline bundle cost."

"Okay, but I'm more concerned with how you define 'a hundred per cent safety factor' on the pipe," Rob said. "It's due to the sea water corrosion over a twenty-year span?"

"Yeah. The hundred per cent factor is an approximation the petroleum industry's found useful, so we'll use it."

"Do I figure the pipe as being corroded to half its thickness to get that hundred per cent safety factor? Or just cut its yield and ultimate tensile strength figures in half?"

"Just cut the figures in half," Jay said.

Rob gathered his notes. "Guess that's all I need," he said. "I'll let you know when I have some conclusions."

UNDERSEA PIPELINE: VERIFICATION OF A STRESS ANALYSIS

Part B: A Stress Man Under a Strain

Rob first approached the problem, using a model shown in Figure 1B, by establishing an approximate distance between the bullnose and the tangency point of the pipeline bundle to the sea floor. He considered each pipe as acting independently of the others in the bundle. His solution showed that the pipes would form an elastic curve, touching the sea floor approximately 90 feet from a vertical plane at the bullnose face. The bending stress in the pipe, he found, was excessive. The pipe would buckle locally in compression at the bullnose junction: in Jay's terms, it would kink.

 Prepared for the Stanford Engineering Case Program by Dean C. Ing with the support of the National Science Foundation.

Next he considered a case in which the four pipes were locked together with stiffener plates such that they would act as a unit. In this case, he found, the tangency point was over 150 feet from the bullnose vertical plane. The stress was still excessive.

Rob's reference texts were at his regular desk, almost half a mile from Jay's office. It would be courting trouble to carry all of his materials to the new location, because union stewards are empowered to insist that such physical labor be done by hourly union men. And the red tape involved in getting his materials crated and moved would have taken up more time than Rob could spare. Besides, Rob knew, he felt more at ease in his own bailiwick where he could borrow a text if he didn't own it.

Rob chose to work at his own desk, for the most part. He telephoned Jay when his first two studies indicated failure of the pipeline bundle. "You needn't worry about the curvature going below a sixty-inch radius, anyhow," he told Jay. "This J-55 material will collapse long before that."

"That's what we thought," Jay admitted. "But project management will be glad to get your figures on it. Can you draft up your work and conclusions so I can submit them?"

Rob agreed to do so. In the meantime, he proposed to work on a possible solution. "All it really amounts to," he explained to Jay, "is a prebent section of the J-55 pipeline bundle in the area adjacent to the wellhead cellar. You'd couple the pipes from the pumping station onto this short prebent bundle with the bullnose probe on the end of it. It shouldn't be too much trouble to prebend them, since a hydraulic bender for two-inch pipe isn't all that massive or expensive."

"Sounds good,Rob," Jay said. "Especially since we can still use the J-55 material."

Rob hurriedly completed another study for inclusion into his preliminary report to the project management people. The critical stresses had been shown to occur at the point where the bundle emerged from the bullnose. Rob decided to determine whether an axial force, either tensile or compressive, imposed on the bundle might reduce this critical (in fact, fatal) bending moment. He found that an axial compression force did reduce the bending moment at the bullnose. However, the critical

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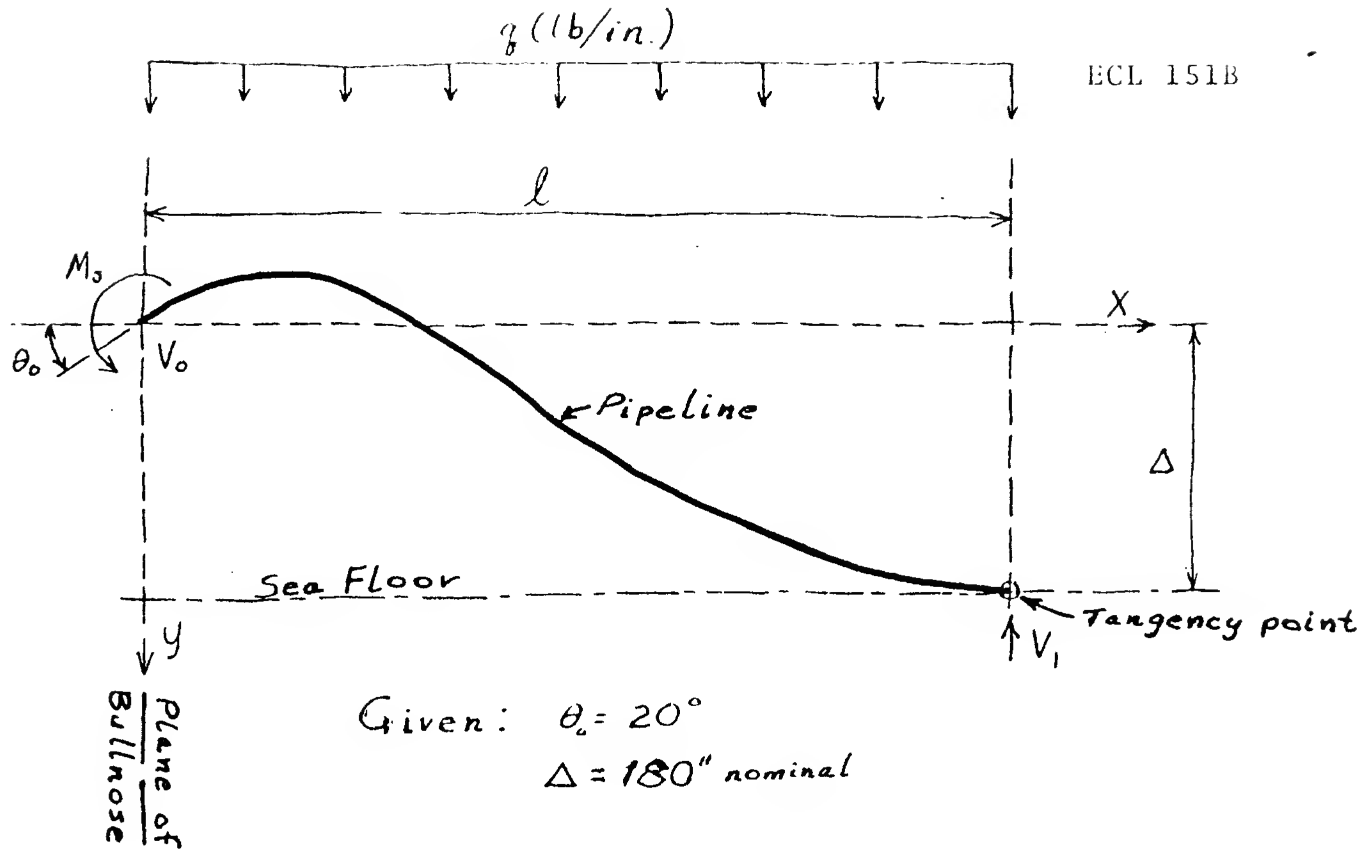


Basic linear beam theory equations: *

$$\frac{d^2M}{dX^2} = \frac{dV}{dX} = -q, \quad M = -EI\frac{d^2y}{dX^2}$$

$$\therefore EI\frac{d^4y}{dX^4} = q$$

where

q = load vertical

V = shear vertical

M = bending moment

EI = bending stiffness

*Stephen P. Timoshenko and James M. Gere, Theory of Elastic Stability (N.Y.: McGraw-Hill Book Co., Inc., 1961), p. 2.

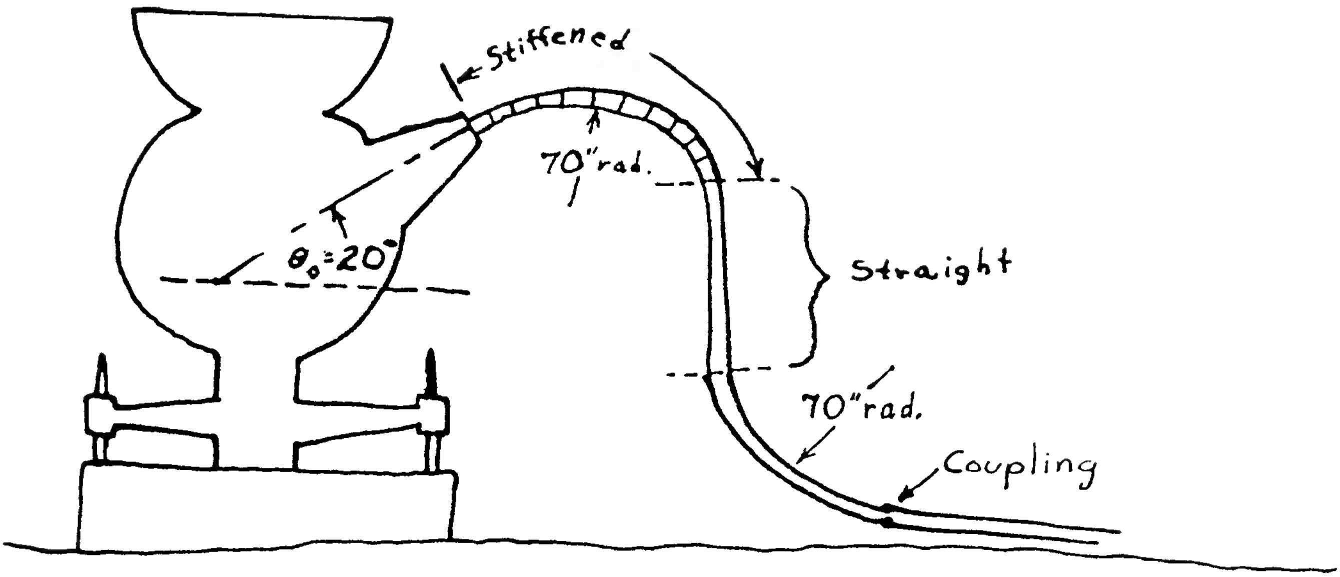
FIGURE 1B

bending moment moved to another location, in the bend where the bundle rises to its highest point before curving back toward the sea floor. This stress was still above the allowable stress; and Rob included this data in his preliminary report.

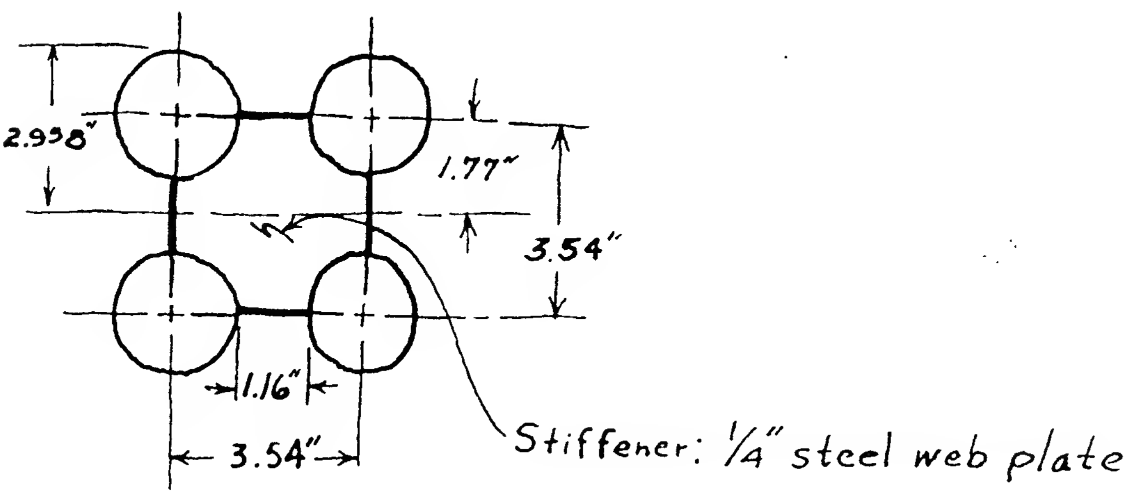
Rob's suggested 'fix' looked good enough to include in the report. It was Rob's idea, as he had mentioned to Jay Hardin, to form a specially prebent termination section on the pipeline bundle as shown in Figure 2B. He also proposed using the stiffener scheme in the portion of the precurved termination section nearest to the bullnose, as shown in Figure 2B. The prebent sections were given radii of curvature sufficiently large (70-inch nominal) to avoid blocking the travel of pumpdown tools. The length of the straight portion of this prebent termination bundle could be varied on the site during the hydraulic bending operation aboard ship, to account for the variations in the bullnose height above the sea floor. However, Rob learned, precise dimensioning of this straight portion was not essential: the distance between the tangency to the sea floor and the bullnose was reduced enough so that the imposed loads were easily survived even if the straight section were a foot too short or too long. And a hurried call to Jay Hardin revealed that, though the bullnose height might vary by three feet on different installations, this height could be measured within about six inches. Therefore, Rob concluded, his requirement for on-site bending of the pipes would not introduce any new close-tolerance difficulties.

By this time a good-natured joke existed between Rob and Jay Hardin. Rob had begun by charging his time to a work-order reserved for such analytical services as his stress work. But as he prepared his own prebent design, Rob slyly suggested that he needed a different work-order to cover his design work! Jay countered by offering him a work-order for outside training, implying that this design exercise was training which Rob needed. Rob, of course, continued using the original work-order.

The prebent termination bundle design, when complete appeared to satisfy all requirements. Maximum stress was again at the point where the bundle emerged from the bullnose probe, but much reduced; the elastic curve of the bundle from its tangency point on the sea floor was greatly shortened. Rob transcribed and formalized his working notes, and submitted his findings to the Undersea Pipeline Project. He acknowledged that, in



Treat stiffened portion as a 4-pipe unit



$I = 21.14 \text{ in.}^4$

$q = 1.662$ lb/in., flooded, incl. web plates

FIGURE 2B

several places, he had used linear beam theory where nonlinear beam theory would have been more ideal. The error, Rob concluded, was insignificant in calculating the elastic curves of this pipe and the stresses in the critical areas.

Rob convened again with Jay Hardin and briefed him on his findings. The special termination section was bound to be slightly more expensive, and would probably draw some criticism on those grounds. But it was a solution, and both men assumed that Rob would return to his old job (and work-order!) as soon as project management gave its blessing to Rob's report. It hardly occurred to either man that the report would not be accepted until Jay was given the task of breaking that unpleasant news to Rob Kinner.

"It's that linear and non-linear beam theory hangup," Jay explained. "The old solutions failed, and your pre-bent design succeeded, all on the basis of linear beam theory. Management is afraid the error introduced by using linear theory might be great enough so that we may be ruling out a cheap solution that would really be okay."

Rob was able to discuss this objection without rancor. He maintained to Jay, and later to project management that stress men conventionally use linear beam theory with perfect confidence when making calculations on a member with a length-to-diameter ratio of less than one hundred. Yes, he recognized that in this case the ratio was several times higher, but in principle it was the same; you recognize a very slight error exists but you can live with it. No, he did not believe that non-linear theory would provide significantly different answers from those he had given.

Why had he not used nonlinear beam theory to make his calculations? "Because," Rob said mildly, "nonlinear solutions are very much more complex; they require computer time, in each case, which involves time and money, which I gather you couldn't afford."

One member of the staff admitted that, not being strong on stress analysis, he felt a bit out of it. What, he wondered, was the critical assumption behind linear beam theory? Rob considered his answer for a moment before replying, "Linear beam theory makes the assumption that the equation for curvature of a member has been linearized; that is, if that curvature were bent back into a straight line, a straight-line projection so to speak, the length of the member would be

unchanged. In nonlinear theory, you're working with much longer or thinner members, and you try to figure the actual change in length which, in theory, is the case. What I'm saying is that in this case, the length change and the force changes that go along with it, are inconsequentially small."

If this satisfied the staff man, the general position of management was unchanged. They wanted very much to have confidence in Rob's work, yet they lacked that confidence. Rob asked if there were funds to support an experiment to verify his stand. Sadly, there were not. Rob left the meeting with the feeling that somewhere, just beyond his fingertips, a solution waited. If he had access to a computer, -- but that was out of the question.

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UNDERSEA PIPELINE: VERIFICATION OF A STRESS ANALYSIS

Part C: A Thousand Expert Opinions

Rob Kinner allowed his dilemma to follow him home that night, a thing that rarely happened. He picked at his supper and at the problem, unwilling to accept the fact that Universal had said, in effect, that an expert's opinion was still only an opinion. Rob was sure that any number of trained stress men would agree with him, but how does a man go about getting a consensus from a dozen such experts?

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As usual, Rob had carefully mapped out his work schedule for that evening (Friday) and the following two days. There was just time, with luck, to install the home sprinkler system in his yard for which, weeks before, he had stockpiled fittings and water pipe. He was in the process of inventory, in his garage, when his thought about all those expert opinions returned. One test, said an old adage, is worth a thousand expert opinions. Universal can't afford a verification test, Rob thought, but maybe I can. He began viewing his lengths of three-quarter-inch steel water pipe in a new light.

For his purposes, the water pipe was nearly identical to the A.P.I. J-55 material. It had an actual nominal O.D. of 1.050 inches, an I.D. of 0.824 inches, and he had well over a thousand linear inches of the stuff on hand. He could couple the pieces into a single length of pipeline to obtain a 'beam' member with a length-to-diameter ratio of a thousand, if need be.

Rob began to whistle as he worked. By supporting this pipe so that it described an elastic curve of several hundred inches, he would have a stressed member which, in theory, could only be analyzed by nonlinear methods. Yet he could attempt a solution by linear beam theory, and check his calculations by actual measurements of force, mass, and distance. If the linear solution agreed very closely with his measured data, he could show that the simple linear beam calculations were acceptable; and that his calculations regarding the pipeline bundle were similarly valid.

Rob had almost everything he needed around the house; and he borrowed a polaroid camera from a neighbor. Before snapping off the light in his garage that night, he took another inventory: pipe, coupling tools, kitchen stool, bathroom scale, chalk, polaroid camera, tape measure, and a thin block of wood.

Saturday morning, Rob first tared the pipe weight. He spent more time coupling pipe than he did on the experiment. Measuring to the center of the pipe, he marked the center point with chalk. He placed the block of wood atop the bathroom scale pad, to serve as a crude 'knife edge' for balancing, and put the scale atop the kitchen stool. Finally he lifted the pipe at its center and placed the chalk mark above the wooden 'knife edge'. The pipe curved away on each side, coming tangent to the driveway some ten yards distant.

The experiment was next photographed; reproductions of Rob's polaroid shots are shown in Exhibit 1C. To determine and mark exact points of tangency of the pipe to the concrete driveway, Rob used a sheet of paper as a feeler gage. His tangency points were accurate to within a fraction of an inch.

Rob's data, and his calculations via linear beam theory, are shown in Exhibit 1C. These pages are reproduced here in substantially the same form as they appeared in Rob's final report to project management. He did not simply thrust this experiment on management without preamble: his first act on the following Monday, was to present his findings informally. The experiment was judged to be as good a proof as could be obtained, and the objections to his earlier findings disintegrated at once.

When Rob Kinner returned to his parent department, it was with the thanks, and full confidence, of the Undersea Pipeline people. Perhaps the most important facet of his experiment, in their eyes, was that it had consumed only a few hours, and negligible funds. But it took Rob another three weeks to get his sprinkler system installed.

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Flowline Pipe Bundle - Experiment

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Pipe Material:

$\frac{3}{4}''\phi$ Std. Galvanized Pipe

$q = 0.096078$ #/in. (24.5# for 21'-3" length)

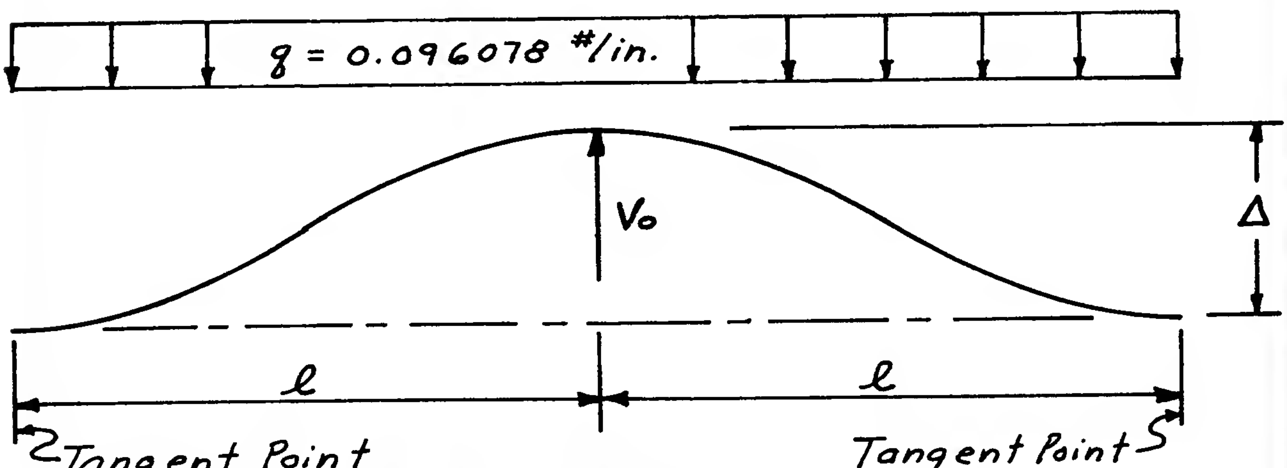
$E = 30 \times 10^6$ psi (assumed for steel pipe)

$I = 0.037 \text{ in}^4$ (from AISC tables for pipe)

$\Delta = 13.5''$ Measured from experiment

$\ell = 324.88''$ Measured from experiment

$V_o = 42.8$# Measured from experiment



Test Set-Up

From Linear Beam Theory

$\ell = [72 E I \Delta / q]^{1/4} = 325.53''$

$\%\text{ Error} = \dfrac{325.53 - 324.88}{325.53} \times 100\% = 0.2\%$

EXHIBIT 1C
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Flowline Pipe Bundle - Experiment

From Linear Beam Theory (Cont.)

$$V_o = 2\left[\frac{128}{9} E I \Delta g^3\right]^{\frac{1}{4}} = 41.7^{\#}$$

$$\underline{\underline{\%\ \text{Error}}} = \frac{42.8 - 41.7}{41.7} \times 100\% = \underline{\underline{2.6\%}}$$

Conclusion:

Based on the excellent correlation between the test results and the linear beam theory (0.2% and 2.6% errors), the use of linear beam theory for the solution of this type of problem is justified.

Photographs of the deflected pipe are shown on page 3.

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Flowline Pipe Bundle - Experiment